

Investigation on the different types of resonators in the thermoacoustic Stirling prime mover

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Abstract

A new thermoacoustic Stirling prime mover consisting of a looped tube and different types of resonators respectively has been built. Experiments were focused on three axisymmetric types of resonators: cylinder, cone and cylinder-cone under the same operation conditions. Pressure ratios in the prime mover were observed, 1.15 for cylinder-cone, 1.092 for cylinder and 1.097 for cone. The acoustic fields along the looped tube and different types of resonators were calculated, which agreed well with the measured results.

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1. Introduction

The traveling wave thermoacoustic prime movers undergoes the same thermodynamic cycle as conventional Stirling cycle. Yazaki et al. [1] succeeded for the first time in constructing a traveling wave thermoacoustic prime mover by using a looped tube. The measured P and U in the looped tube shown that a phase lead Φ between P and U was closed to a traveling wave phase in the regenerator. In 1999, Backhaus and Swift [2] jointed a 1/4-wavelength resonator in a looped tube, and upgraded a thermal efficiency up to 0.30. After that, Ueda et al. studied a same type prime mover on intense acoustic wave by varying the lengths of the looped tube and the resonator as well as the position of the regenerator [3]. We also constructed a thermoacoustic Stirling prime mover in 2001 [4]. Two different acoustic modes, high frequency mode and low frequency mode, were observed. However, the mentioned works were paid little attention to the influence of geometry on pressure ratio.

In this paper, a new thermoacoustic Stirling prime mover consisting of a looped tube and different types of

resonators respectively has been built. Experiments were focused on three axisymmetric resonators in shapes of cylinder, cone and cylinder-cone under the same mean pressure and uniform heater power to investigate the influence on pressure, temperature acoustic distribution. Furthermore, the models with different types of resonators were calculated, and the results compared with experimental ones, which were qualitatively in good agreement.

2. The experimental setup

The thermoacoustic Stirling prime mover is illustrated in Fig. 1a, with pressure transducers P1–P10 and four thermocouples T1–T4 in Fig. 1b. A T-type connector jointed the looped tube with the resonator, where $x = 0$ was set as an origin point, and the positive direction of x was taken anticlockwise in the looped tube, and the negative direction of x was towards the resonator, respectively. The lengths of the looped tube and the resonator were 0.84 and 1.6 m, respectively. Three types of resonators were axisymmetric, and were described by the following equations. For the cylinder, the radius was

$$r(x) = 0.034 \quad \text{for} \quad -1.6 \leq x \leq 0. \quad (1)$$

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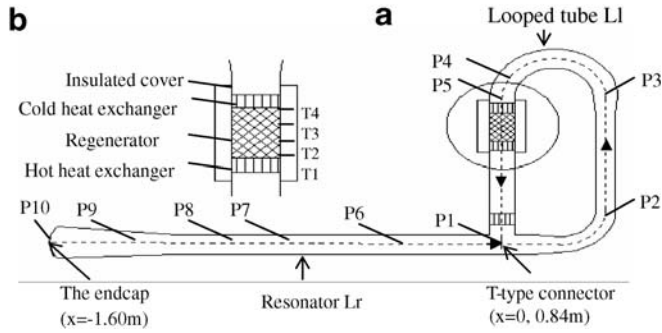


Fig. 1. (a) The thermoacoustic Stirling prime mover; (b) Thermoacoustic core.

For the cone, the radius was given by;

$$\begin{aligned} r(x) &= 0.102 \quad \text{for } -1.6 \leq x \leq -1.4 \\ r(x) &= -0.0486x + 0.034 \quad \text{for } -1.4 \leq x \leq 0 \end{aligned} \quad (2)$$

The geometry of the cylinder-cone was:

$$\begin{aligned} r(x) &= 0.07 \quad \text{for } -1.6 \leq x \leq -1.4 \\ r(x) &= -0.18x + 0.034 \quad \text{for } -1.4 \leq x \leq -1.2 \\ r(x) &= 0.034 \quad \text{for } -1.2 \leq x \leq 0 \end{aligned} \quad (3)$$

The cold heat exchanger was brass plates of 0.5 mm in thickness and 21 mm in height. The mean pressure was 1.3 MPa nitrogen gas, and heater power was 500 W in the following experiments.

3. Results and discussion

The position of the maximal oscillating pressure amplitude was at P3 independent on the types of resonators. The peak-to-peak pressure amplitudes for the cylinder, the cone and the cylinder-cone were 114 kPa, 120 kPa and 143 kPa, the pressure ratio, namely the maximum pressure to the minimum pressure, were 1.092, 1.097 and 1.15, respectively, which demonstrated the effects of resonator geometries.

One-dimensional inviscous momentum equation for compressible gas can be expressed as [5]

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x}, \quad (4)$$

where $u \frac{\partial u}{\partial x}$ is nonlinear term, which stands for a non-zero velocity gradient along the resonator. For cylinder and cone resonator, the nonlinear term increases because of nonlinear effect including harmonics, and acoustic power shift from the fundamental mode to higher harmonic mode. However, using cylinder-cone resonator can significantly decrease the velocity gradient so that $u \frac{\partial u}{\partial x}$ can be decreased or even eliminated. Therefore, performance of the system with a cylinder-cone resonator can be improved effectively.

Based on low-amplitude acoustic approximation, experimental measurements were compared with calculated results. The values of p were plotted in Fig. 2a and b as

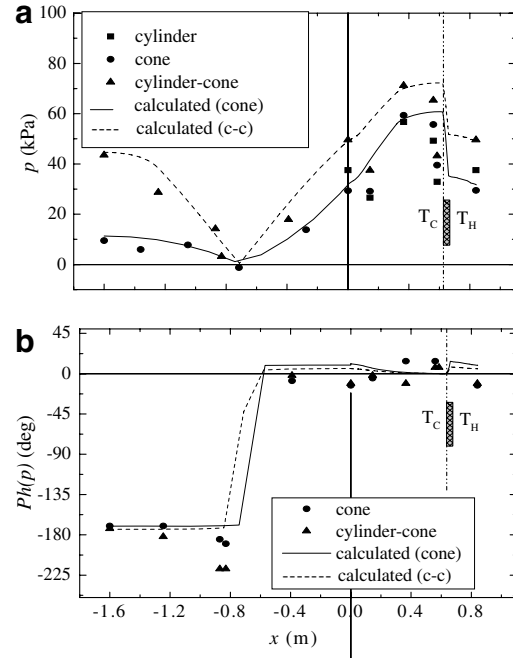


Fig. 2. Comparisons of measured and calculated results: (a) the pressure amplitude and (b) pressure phase. c-c stands for cylinder-cone

the function of position x in the present system. As shown in Fig. 2a, the pressure amplitude in a looped tube increased as x increasing from 0 to 0.56 m, and then it decreased sharply through the thermoacoustic core. It was inferred that a quarter-wavelength mode was excited in the present prime mover. The pressure amplitude at P5 was markedly much smaller than at P4, because a jet pump was inserted into the space between P4 and P5, which was not present in Fig. 1. Both the pressure amplitudes of measured and calculated results along a looped tube for the cylinder-cone type were larger than ones for cone type. Cylinder-cone type improved the pressure amplitude effectively. In addition, pressure distribution in the resonators was affected by the types of resonators. The values of p decreased and then increased as x changing from -1.6 to 0 m. The pressure amplitude had the node at $x = -0.715$ m, and the antinode at the endcap of resonator for both cone type and cylinder-cone type. The mode in the resonator was between a quarter-wavelength mode and a half-wavelength mode. In all cases, measured results were in good agreements with calculated ones. Here, the phase at the endcap of resonator (at P10) was set as reference point of phase angle in order to compare phase distribution in the present thermoacoustic prime mover. Both experimental and calculated phase angles at P10 were equal to zero, and then the experimental and calculated phase angles of P1–P9 were compared each other. The phases under both conditions of cylinder-cone type and cone type were changed from nearly -180° to 0° in the resonator. In addition, comparisons of important parameters including frequency, the peak-to-peak pressure amplitude, pressures ratio and temperature difference of regenerator with three

Table 1
Comparisons of measured and calculated results

Method	f (Hz)	Peak-to-peak (kPa)	$\frac{p_{\max}}{p_{\min}}$	$\frac{T_H}{T_C}$
<i>Cylinder</i>				
Measured	75.5	114	1.092	2.71
Calculated	79.1	122	1.1	2.17
<i>Cone</i>				
Measured	74.6	120	1.097	2.33
Calculated	64.1	144	1.16	1.91
<i>Cylinder-cone</i>				
Measured	62.5	143	1.15	2.01

types of resonators are shown in Table 1. With cylinder-cone type, resonant frequency decreased and a higher pressure ratio was acquired at a lower the temperature difference of regenerator in the system.

4. Summary

Three types of resonators: cylinder, cone and cylinder-cone influence on pressure waveform and acoustic field in the system were investigated. The measured results were in good agreement with calculated ones. The results indicated that the moderate type of resonator improved pres-

sure ratio and decreased temperature difference of regenerator for maintaining the self-excited resonance.

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